

Cleaning and Household Robots: a Technology Survey

Paolo Fiorini

*Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109, USA*

Erwin Prassler

*FAW - Research Institute for
Applied Knowledge Processing
89081 Ulm, Germany*

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Abstract. This paper describes some of the main technology areas that have been actually used in the development of cleaning robots. The approach taken in this survey is to examine the characteristics of cleaning robots that have made successful laboratory demonstration or have become commercial products. We then identify the technology approach followed by the authors, and group their contributions in a few general areas. The result is a summary of used approaches to the solution of difficult, albeit very practical, problems in the area of autonomous execution of cleaning tasks.

Keywords: Mechanical configuration, design requirements, control architecture, complete coverage

1. Introduction and Motivation

Cleaning Robots are among the first members of the service robot family to reach the marketplace with practical and economical solutions. Cleaning an indoor area is a challenging practical and theoretical problem whose solution involves all the basic research areas in robotics and lots of common sense. It has also assumed the status of a litmus test for robotics systems, and "robotic vacuum cleaner" is a favorite research and development topic.

So far, useful results are scarce because of a combination of technical and economic factors. This paper identifies the main technical elements contributing to the design of a cleaning robot and provides a summary of the technologies actually used in the design of this specific service robot.

The paper is organized as follows. Section 2 describes some of the mechanical configurations used. Section 3 presents a list of design requirements and discusses some of the control architectures used. Section 4 discusses navigation algorithms specifically designed to provide complete coverage of areas to be cleaned by the robot. Section 5 de-



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scribes some of the solutions for interacting with the environment, and Section 6 discusses some of the approaches to interface with the human users. Finally, Section 7 summarizes the paper and identifies specific research areas that have not been addressed so far.

2. The body

In general, when thinking of cleaning robots, the image of an iron maid comes to mind, such as the Quasar Industries prototype, Klatu (u-talk spelled backwards), unveiled in the late 1970s to help with domestic chores. Cleaning robots however, can take different forms depending on their working domain, and different shapes have in fact been proposed for household and industrial use, or for use in crowded areas, in corrosive environments, or at the bottom of a pool.

A study of different mechanical shapes for such a robot is presented in (Ulrich et al., 1997), stating that a home cleaning robot be small, capable of moving under typical furniture and able to make tight turns in small apartments. Figure 2 shows three typical configurations for the robot body, where the cleaning device is marked by a thicker line. Figure 2-a shows a basic rectangular-shaped robot, Figure 2-b shows a circular cleaning device, and Figure 2-c shows a robot equipped with a cleaning arm.

The main considerations in designing the body of a cleaning robot have to do with efficiency in carrying out the cleaning task. Most robots are in fact capable of complete floor coverage, but only few shapes allow an efficient coverage. From this point of view, the shape of Figure 2-a is the least suitable for a cleaning task, since it requires complex navigation maneuvers to reach in corners and around obstacles. Similarly, round robot cannot clean in corners, even though their shape makes navigation around obstacles a little easier. The best compromise, according to (Ulrich et al., 1997) is the shape shown in Figure 2-c, where a cleaning arm offers a wider range of solutions to cleaning and navigation. Since the cleaning head is independent of the robot body, navigation and cleaning are partially decoupled. Whole body maneuvers can then be used to clean large free areas, whereas corners and tight spaces surrounding obstacles are cleaned by moving the arm while keeping the robot body stationary.

3. The mind

To approach robotic cleaning from a scientific point of view, it is essential to define a set of specifications to guide the development (Jenkins, 1993). These requirements can be grouped in the following categories:

Environment considerations. Typical environments inhabited by humans, such as houses, offices, commercial and industrial buildings, impose very stringent constraints on the working modes of a cleaning robot. Rooms are usually configured randomly, doors may lead to closets as well as to other rooms, wall openings may be dangerous places, such as stairwells or fireplaces, and different furniture require specific approach maneuvers. Furthermore, humans and animals may try to interact with the robot.

Commercial and legal considerations. Installation procedure must be simple, involving only the mapping of the house and not a significant engineering effort to make it robot-friendly. Maintenance should be reduced to a minimum, all possible malfunctions should be dealt with gracefully, and the robot must be extremely safe. The cost of the robot should be comparable to a high-end home appliance.

Operational requirements. The robot should be capable of fully autonomous operation, including autonomous use of a simple charging station. It should also have a straightforward operator interface. Normal operation should be very simple, based on regularly scheduled cleaning sessions, or by simple telecontrol.

Sensor requirements. Sensors will need to be self-calibrating and able to guarantee a complete coverage of the environment, enabling the robot to do mapping, position estimation, obstacle detection and collision avoidance, and to deal with possible emergencies.

Reasoning requirements. To carry out successfully the above operations, the robot will need to be able to perform at least the following four tasks: *i)* Exploration and mapping must be autonomous and incremental, able to differentiate static from movable obstacles, and allowed from forbidden floor space. *ii)* Path planning and execution is a well known operation, but the inclusion of energy optimization, time minimization, and vacuuming task execution may make it more complex. *iii)* Operational contingencies may be non time-critical, such as commands from the owner, blocked path, minor hardware failures, whereas other problems may require an immediate response especially when they affect safety. *iv)* Operator Interface will be a challenging problem, since the robot will deal with technically naïve people, who may have malevolent and/or careless behavior.

According to (Elgot-Drapkin et al., 1993), the logic mechanism that the robot will implement will have to extend some aspects of traditional

monotonic logic. Important additions to classical logic should include the capability of relating lexical expressions to environmental positions (embedded logic), of dealing with unexpected events and classify their importance (common-sense logic), of keeping track of the passage of time (deadline-sensitive logic), of making sense of discordant input (contradiction-tolerant logic), of making sense of ambiguous commands (semantic shift logic), and finally of being time conscious, i.e. its logic inference mechanism should be fast and narrow.

The definition of a suitable architecture supporting robotic cleaning tasks is a difficult question. A rather complete survey of task planning methods for sensor-based robots is presented in (Chen and Trivedi, 1995) where the main elements concurring in the generation of a plan are identified as: integration of sensing and action, hierarchical planning, re-planning, error recovery, interrupt handling, conditional and iterative planning, learning, and integration of planning and simulation. The typical approach is a three level structure in which the bottom level interacts with the world using reactive strategies (executive level), the middle level employs symbolic strategies to perform simple logical operations on sensor data (tactical level), and the top level (strategic level) performs planning and reasoning (Gray, 1996), as shown in Figure 3-a. Reference (Firby, 1993) discusses an implementation of the middle layer called RAP which is an intermediary between the plans developed by the top level and the needs of the execution layer, as shown in Figure 4. RAP is also a simple planner/executive on its own to compensate for the limitations of the other two layers.

Behavior-based control architecture have the general structure shown in Figure 3-b. An example is AuRA (MacKenzie and Balch, 1993), which can deal with uncertain and partially specified domains. The modularity of subsumption-based architectures, such as AuRA, simplifies the addition of new features to a basic cleaning behavior. The *vacuuming* behavior, for example, is implemented by modifying the standard *foraging* behavior, with the robot actively seeking dirt, detecting it and acquiring it using a vacuum action.

The Architecture for Behavior Based Agents (ABBA) (Jung et al., 1997) has been demonstrated in the context of two robots performing coordinated cleaning operations with meeting at predetermined locations and cooperative actions. The behavior of the complete system is expressed as a network consisting of two types of nodes: Competence Modules (CM) and Feature Detectors (FD). A CM becomes active when all its preconditions are satisfied and it has the highest activation level among all the ready CM. The preconditions are supplied by the FD modules, providing the interface with the environment. The activations are continuously updated by a spreading activation algorithm. The

network can be activated or inhibited by external sources, by means of rules representing activation by situation and by goal, and inhibition by goal. Within this behavior based architecture, navigation is achieved by a combination of geometric and topologic representations. Geometric locations are represented by FD's which provide preconditions for CM representing some motion of the robot. Topology is introduced in the representation by recording the trajectories executed by the robot into a connectivity map of the environment. The conjunction of distributed planning and geometrical/topological representation permits the formulation and execution of complex plans in which robots interact and cooperate with each other interleaving their respective actions.

Whether using a layered or a behavior based architecture, planning for a vacuum task must include a careful balanced compromise of reactive and deliberative planning. In a layered architecture, the reactive component acts as a filter on the planned task activating or deactivating subtasks depending on the sensor status. On the other hand, in a behavior-based architecture, sensor-driven, competing behaviors will determine the evolution of the vacuuming operation. Comparing the performance of the two architectures shows that time bounds, i.e. time given to the planner to devise a new plan, is the critical factor in determining the robot performance (Blythe and Reilly, 1993). A highly dynamic environment can be dealt with only by an architecture including a high level of reactivity. However, this will be at the expense of plan quality, since interactions and implications of various actions will not be examined in detail.

Finally, to complete the cleaning operation, one must provide a metric to evaluate cleaning quality. A complex methodology for measuring, understanding and thus predicting the contribution of software components is discussed in (Bonasso, 1993), with reference to the household vacuuming domain. This methodology relies on the statistical analysis of experimental data and therefore it may be more appropriate for the characterization of commercial than household devices. Another form of performance analysis proposed for the cleaning domain includes a metrics based on efficiency, robustness, safety and robot usability (Musliner and Kortencamp, 1993), and is more suitable for testing the human factor aspects of a robotic cleaner.

4. The Cleaning Navigation

In a real cleaning robot, experiments prove that navigation is mostly affected by the following elements (Ulrich et al., 1997): obstacle identification, working hypothesis, map creation, and environment description.

Obstacle identification can be limited to a few large classes, such as *legs*, *walls*, *corners*, and *unidentified*. Legs are all those objects that can be cleaned around, walls are obstacle with a long straight edge, corners are the conjunction of two walls, and unidentified are all the objects not falling in one of these categories. Two important benefits are drawn from this initial exploration of a room. A simple *local* occupancy map can be built using this information. Then, obstacle identification allows the robot to use hypothesis to determine the best cleaning strategy. The most critical element of this process is the creation of the environment map. A possibility is to first contour the room and then explore its interior, integrating the local maps describing the obstacles with the contour map of the room. The contour map will be used by the robot to self-localize, in case it gets lost. The map could be discretized and each element marked with a number representing whether the element is occupied or not, and its cleaning schedule. This representation is then used by the robot to determine its cleaning pattern and trajectory around the room. The environment map can be enhanced by a list representation of the room's major elements. For example, the room perimeter can be represented by a list of its corners, obstacles may group nearby legs, characterized by location, size, and cleaning pattern. Periodically during its operation, the robot must carry out a correction phase, to ensure that the map is consistent with the geometrical hypothesis about the room and tracks the unavoidable changes in obstacle position.

The most important question about automatic cleaning is the coverage achieved, i.e. whether it is possible to determine an obstacle avoiding path that can clean a high percentage of the surface floor. The technical literature has several references to this problem, appropriately called the *complete coverage problem*, and to methods and path templates that can guarantee an efficient coverage.

A possible approach to solve this problem is to devise a set of standard maneuvers and to try to combine them appropriately, depending on the shape of the room (Hofner and Schmidt, 1995; Neuman de Carvalho et al., 1997). This approach is best suited for cases where the room configuration remains mostly unchanged, since it pays to invest in optimizing the trajectory in a mostly fixed environment. It consists of defining several basic path planning templates, depending on the kinematics of the cleaning robots and on the structure of the environment. Then the planning algorithm constructs a *technologically feasible* cleaning path using the templates. With each template, a geometric motion corridor is defined, rectangular, circular, or combined, which is used for map-based collision analysis between the robot and the known contours of the environment. Typical trajectories have a *snake-trail* pattern, with

overlapping tracks. This approach avoids the complications of dealing with non-holonomic constraints while planning the robot trajectories. Self localization can be achieved by landmark detection combined with a map of the environment and a tree representing the expectation of the sensor readings within the uncertainty of the actual robot position. The use of templates in case of obstacles with variable position is examined in (Neuman de Carvalho et al., 1997) where it is shown that complete coverage can still be achieved by simply following the contour of the unexpected obstacle until the robot returns on the the original path.

Another approach to the coverage problem is cell decomposition and search, where complete coverage is equivalent to exhaustive search of the space (Pirzadeh and Snyder, 1990). This can be achieved by creating an artificial potential field by assigning a numerical value to each cell, by increasing the value of a visited cell, and by taking the next step to the cell with the lowest value among the adjacent cells.

Other complete coverage algorithms based on assigning specific numeric values to the elements of a cell decomposition are presented in (Zelinsky et al., 1993). The underlying philosophy is that the numeric value assigned to each cell is a function of the distance to the goal and of additional constraints aiming at reducing the number of turns performed by the robot. In its straightforward implementation, the cell value is simply the distance from the goal, however this approach results in a very unpractical trajectory, with a large number of turns, as shown in Figure 7-a. A better algorithm for assigning numerical values to cells accounts for trajectory difficulty in terms of distance from the obstacles and of curve smoothness. The potential field defined in this way generates numerical values for each cell with better convergence and trajectory smoothness, as shown in Figure 7-b.

The idea of templates is used in (Choset and Pignon, 1997) by adapting a single template, i.e. the back and forth motion typical of a plowing ox, to an appropriate cell decomposition of the environment. This approach combines the advantages of cell decomposition with the template approach and minimizes the number of cells used by requiring the creation of a new cell only when the topology changes, as shown in Figure 8. The cell decomposition is then represented with an adjacency graph, which can be searched with depth-first like algorithms to find an optimal path visiting each node in the graph.

Complete coverage could also be achieved in real time by making the robot mark its path with a heat trail, and then avoid areas previously marked (Russell, 1993). In this way, the robot can, in principle, construct the complete coverage incrementally, without visiting twice the same floor locations.

5. The interaction with the Environment

Sensing and actuation are the primary methods used by cleaning robots to interact with the environment and, in fact, technologies such as force control, were developed with window cleaning in mind. It is then useful to briefly present significant examples of sensing and control applied to the cleaning domain. A representative example of advanced environment interaction, is described in (Khatib et al., 1996; Khatib, 1999), where mobility is coupled to manipulation to create the prototype of a robotic assistant, which is demonstrated in experiments of domestic chores. A different cleaning operation is described in (Zhou and Skibniewski, 1994), and consists of an application of force control to the clean-up of a construction site, a task similar to wallpaper scraping or wall washing in the household domain. It must be noted that in these application of mobile manipulation, the position of the mobile base must also be controlled within the force loop, since its possible inclination with respect to the wall will proportionally vary the applied force.

Visual sensing can also be used as a control device for robotic navigation. Reference (Jarvis, 1994) describes the operation of a group of mobile robots involved in the cooperative cleaning of an experimental environment. Robot position is monitored by an overhead camera, a simple step of environment engineering that perhaps can be tolerated. A central controller monitors and directs the operation of single and multiple robots, whose position is mapped to the video plane of the observing camera. More traditional use of vision for cleaning tasks is described in (Rivlin and Rosenfeld, 1995), which summarizes all the visual functions necessary for vision-based control of cleaning, such as using walls as references to follow a corridor, recognizing small mobile obstacles and large static obstacles.

6. The Operator Interface

A critical form of interaction between the robot and the rest of the world is human interaction. As discussed in (Khatib et al., 1999), the success of the introduction of even simple robots, such as cleaning devices, into a human environment will depend upon the development of competent and practical systems that are dependable, safe and easy to use. During a cleaning task, the robot must be capable of performing basic autonomous navigation functions safely and with a carefully planned interaction with its human owner.

Simple household cleaning robots will be mostly stand-alone machines interacting with their human owners by voice commands or by TV remote-like controllers. Robots must be able to accept commands from the owner coming from a variety of sources, the simplest of which could be a push button, but it also should be able to provide intelligent feedback regarding the advancement of the cleaning task and its own status (Ettelet et al., 1998). These issues can be grouped into two main classes: the first is the achievement of a high level of interaction between human and robot, and the second is the specific integration of humans into the robot control structure (Wilkes et al., 1999). A satisfactory solution would try to balance the robot capability to handle repetitive tasks with the human intelligence and perception. Simple cleaning robots may be equipped with a small keyboard to initiate room mapping and to carry out the cleaning task, whereas more sophisticated devices may be able to interact with their owners in more complex forms. Current prototypes implement only a simple interface, relying on a mixture of random motion generation and planned trajectories to clean a room. In dealing with humans, robots must exhibit knowledge of many domains, and it is challenging to find the right compromise between development time and robot level of user friendliness. Contacts between robot and people in the household have been the subject of study and simulations in the context of exchange of objects (Agah and Tanie, 1999). In the specific case of cleaning robots, the most likely contact will be an impact due to wrong modeling or sensor limitations. The robot must then be equipped with passive protection means and with fast reactive backtracking to minimize the impact force. Furthermore, suitable visual warnings should be installed in the body, to prevent accidental tripping over the robot.

7. Conclusion

In this paper we summarize some of the most significant technologies actually used in the design of home cleaning robots. The intention of this survey is to take a snapshot of the robotic technologies that have been applied so far to the cleaning domain. Clearly, robotic cleaning being a complex task, all robotic technologies are potentially applicable to this domain. However, by restricting the survey only to technologies described in the technical literature on cleaning robots, we are assured of taking a realistic picture of technologies that have made the cross-over from the laboratory to the household.

Two main technology areas have emerged as those that have been studied the most: architectural analysis and complete coverage nav-

igation. In the first area, several models have been described and, because of the domain characteristics, the trade-off between different approaches have been clearly identified. In the second area, several methods to achieve complete coverage have been presented. The emphasis is on the development of methods achieving full coverage with smooth trajectories thus implicitly optimizing some of the performance indices of cleaning tasks.

The survey has also shown the lack of literature in the areas of sensor and sensor fusion for cleaning. It is conceivable then, that the two main stumbling blocks to the development of this field will be the lack of appropriate sensors for the detection of dirt, and thus the inability to optimize time and efficiency, and safety during the interaction with the humans, thus limiting the use of cleaning robots because of possible liability concerns.

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References

- Agah, A. and K. Tanie: 1999, 'Interaction of and anthropomorphic simulated human with a simulated service robot'. *Simulation* **72**(1), 12–19.
- Blythe, J. and W. Reilly: 1993, 'Integrating Reactive and Deliberative Planning in a Household Robot'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 6–13.
- Bonasso, R.: 1993, 'What Good is your Vacuum Robot's Intelligence'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 14–18.
- Brittain, R. and B. D'Ambrosio: 1993, 'Autonomous Vacuum Cleaners Must be Bayesian'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 19–22.
- Brutzman, D.: 1993, 'Beyond Intelligent Vacuum Cleaners'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 23–25.
- Burhanpurkar, V.: 1993, 'Design of Commercial Autonomous Service Robots'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 26–33.
- Chen, C. and M. Trivedi: 1995, 'Task planning and action coordination in integrated sensor-based robots'. *IEEE Transactions on Systems, Man, and Cybernetics* **25**(4), 569–591.
- Choset, H. and P. Pignon: 1997, 'Coverage Path Planning: The Boustrophedon Cellular Decomposition'. In: *Proceedings of the International Conference on Field and Service Robotics*. Cambera, Australia.
- Coombs, D.: 1993, 'RoboVac and the Cat will get along famously'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 34–36.

- Crisman, J.: 1993, 'Multiple, Cooperating, Simple Agents for the area coverage problem'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 37-41.
- Crowley, J.: 1996, 'Integration and Control of Reactive Processes'. In: *Proceedings of IEEE Workshop on Intelligent Planning and Control Systems for Service Robots (ICRA'96)*. Minneapolis, MN, pp. 9-16.
- Dario, P., E. Guglielmelli, V. Genovese, and M. Toro: 1996, 'Robot assistants: applications and evolution'. *Robotics and Autonomous Systems* **18**, 729-766.
- Doty, K. and R. Harrison: 1993, 'Sweep Strategies for a Sensor-Driven, Behavior-Based Vacuum Cleaning Agent'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 42-50.
- Elfes, A.: 1996, 'Skill acquisition by Autonomous Robots using a multi-level Control Architecture'. In: *Proceedings of IEEE Workshop on Intelligent Planning and Control Systems for Service Robots (ICRA'96)*. Minneapolis, MN, pp. 17-23.
- Elgot-Drapkin, J. et al.: 1993, 'Vacuum-Logic'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 51-54.
- Ettelet, E., R. Furtwängler, U. Hanebeck, and G. Schmidt: 1998, 'Design issues of a semi-autonomous robotic assistant for the health care environment'. *Journal of Intelligent and Robotic Systems* (22), 191-209.
- Evans, J.: 1996, 'Sensor Fusion and Geometric Reasoning in Mobile Robots'. In: *Proceedings of IEEE Workshop on Intelligent Planning and Control Systems for Service Robots (ICRA'96)*. Minneapolis, MN, pp. 33-41.
- Feiten, W.: 1996, 'Technology requirements for advanced service robots'. In: *Proceedings of IEEE Workshop on Intelligent Planning and Control Systems for Service Robots (ICRA'96)*. Minneapolis, MN, pp. 69-77.
- Firby, R.: 1993, 'An Architecture for a Synthetic Vacuum Cleaner'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 55-63.
- Gat, E.: 1993, 'Design for an autonomous vacuum'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 64-65.
- Gavin, A.: 1993, 'A fast, cheap and easy vision system for an autonomous vacuum cleaner'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 66-75.
- Gips, J. and D. Green: 1993, 'Trying to KISS with the robot vacuum cleaner'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 66-75.
- Gomi, T.: 1996, 'An effective approach to the development of service robots'. In: *Proceedings of IEEE Workshop on Intelligent Planning and Control Systems for Service Robots (ICRA'96)*. Minneapolis, MN, pp. 69-77.
- Gray, J.: 1996, 'Recent development in advanced robotics and intelligent systems'. *Computing and Control Engineering Journal* pp. 267-276.
- Hedler, J. and O. Seeliger: 1993, 'Exploring Vacuuming as a domain of applicability for a reactive planning system'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 79-80.
- Hofner, C. and G. Schmidt: 1995, 'Path Planning and guidance techniques for an autonomous mobile cleaning robot'. *Robotics and Autonomous Systems* **14**, 199-212.
- Horswill, I.: 1993, 'Lightweight Vision -or- How I learned to Stop Worrying and Love my Camera'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 76-78.

- Hoyer, H.: 1996, 'user-oriented control of smart wheelchairs and navigational intelligence'. In: *Proceedings of IEEE Workshop on Intelligent Planning and Control Systems for Service Robots (ICRA '96)*. Minneapolis, MN, pp. 51-59.
- Jarvis, R.: 1994, 'Video Plane Robot Swarms'. *Journal of Robotics and Computer-Integrated Manufacturing* 11(4), 249-258.
- Jenkins, F.: 1993, 'Practical requirements for a domestic vacuum-cleaning Robot'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 85-90.
- Jung, D., G. Cheng, and A. Zelinsky: 1997, 'Robot Cleaning: and application of distributed planning and real-time vision'. In: *Proceedings of the International Conference on Field and Service Robotics (FSR '97)*. Camberra Australia.
- Kawamura, K.: 1996, 'Service Robotics: State of the Art'. In: *Proceedings of IEEE Workshop on Intelligent Planning and Control Systems for Service Robots (ICRA '96)*. Minneapolis, MN, pp. 1-8.
- Khatib, O.: 1996, 'Mobile Manipulation: the Robotic Assistant'. In: *Proceedings of IEEE Workshop on Intelligent Planning and Control Systems for Service Robots (ICRA '96)*. Minneapolis, MN, pp. 42-50.
- Khatib, O.: 1999, 'Mobile manipulation: the robotic assistant'. *Robotics and Autonomous Systems* (20), 175-183.
- Khatib, O. et al.: 1996, 'Coordination and Decentralized Cooperation of Multiple Mobile Manipulators'. *Journal of Robotic Systems* 13(11), 755-764.
- Khatib, O. et al.: 1999, 'Robots in Human Environments: Basic AUtonomous Capabilites'. *The International Journal of Robotics Research* 18(7), 684-696.
- Kurabayashi, D., J. Ota, T. Arai, and E. Yoshida: 1996, 'Cooperative Sweeping by multiple mobile robots'. In: *Proceedings of the IEEE 1996 International Conference on Robotics and Automation (ICRA '96)*. Minneapolis, MN, pp. 1744-1752.
- Lee, W.: 1993, 'Spatial Semantic hierarchy framework for vacuuming robots'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 91-92.
- MacKenzie, D. and T. Balch: 1993, 'Making a clean sweep: behavior-based Vacuuming'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 93-98.
- Milios, E.: 1996, 'Navigation and Environmental Mapping by Mobile Robots'. In: *Proceedings of IEEE Workshop on Intelligent Planning and Control Systems for Service Robots (ICRA '96)*. Minneapolis, MN, pp. 24-32.
- Miller, D.: 1993, 'Cleaning up with second hand sensing'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 99-100.
- Mital, A., M. Kulkarni, R. Huston, and S. Anand: 1997, 'Robot cleaning of underground liquid storage tanks: Feasibility and design considerations'. *Robotics and Autonomous Systems* (20), 49-60.
- Musliner, D. and D. Kortencamp: 1993, 'MICE and the science of vacuuming'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 101-104.
- Neuman de Carvalho, R., H. Vidal, P. Vieira, and M. Ribeiro: 1997, 'Complete coverage path planning and guidance for cleaning robots'. In: *Proceedings of the IEEE International Symposium on Industrial Electronics*. Guimaraes, Portugal.
- Pirzadeh, A. and W. Snyder: 1990, 'A Unified Solution to Coverage and Search in Explored and Unexplored Terrains unsing indirect control'. In: *Proceedings of the*

- IEEE 1990 International Conference on Robotics and Automation (ICRA'90)*. Raleigh, NC, pp. 2113–2119.
- Prassler, E., E. Stroulia, M. Strobel, and T. Kämpke: 1997, 'Mobile Robots in Office Logistics'. In: *Proceedings of the 1997 International Conference on Advanced Robotics (ICAR'97)*. Monterey, CA.
- Rivlin, E. and A. Rosenfeld: 1995, 'Navigation Functionalities'. *Computer Vision and Image Understanding* **62**(2), 232–244.
- Russell, R.: 1993, 'Mobile Robot Guidance using short-lived heat trail'. *Robotica* **11**, 427–431.
- Slack, M.: 1993, 'Fido's Adventures'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 105–108.
- Ulrich, I., F. Mondada, and J. Nicoud: 1997, 'Autonomous Vacuum Cleaner'. *Robotics and Autonomous Systems* **19**, 233–245.
- von Seelen, W.: 1996, 'An Autonomous Robot-System in a Neural Architecture'. In: *Proceedings of IEEE Workshop on Intelligent Planning and Control Systems for Service Robots (ICRA'96)*. Minneapolis, MN, pp. 60–68.
- Webber, B. and N. Badler: 1993, 'Introducing real-world vacuumers'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 109–115.
- Wilkes, D. et al.: 1998, 'Towards socially intelligent service robots'. *Applied Artificial Intelligence* **12**(7-8), 729–766.
- Wilkes, D. et al.: 1999, 'Designing for human-robot symbiosis'. *Industrial Robot* **26**(1), 49–58.
- Yaguchi, H.: 1996, 'Robot introduction to cleaning work in the East Japan Railway Company'. *Advanced Robotics* **10**(4), 403–414.
- Yamamoto, M.: 1993, 'SOZZY: a hormone-driven autonomous vacuum cleaner'. In: *Proceedings of AAAI 1993 Fall Symposium Series: Instantiating Real-World Agents*. Raleigh, NC, pp. 116–124.
- Zelinsky, A., R. Jarvis, J. Byrne, and S. Yuta: 1993, 'Planning paths of complete coverage of an unstructured environment by a mobile robot'. In: *Proceedings of 1993 International Conference on Advanced Robotics (ICAR'93)*. Tokyo, Japan.
- Zhou, Y. and M. Skibniewski: 1994, 'Construction Robot Force Control in Cleaning Operations'. *Journal of Aerospace Engineering* **7**(1), 33–49.



Figure 1. A 1970 concept prototype.

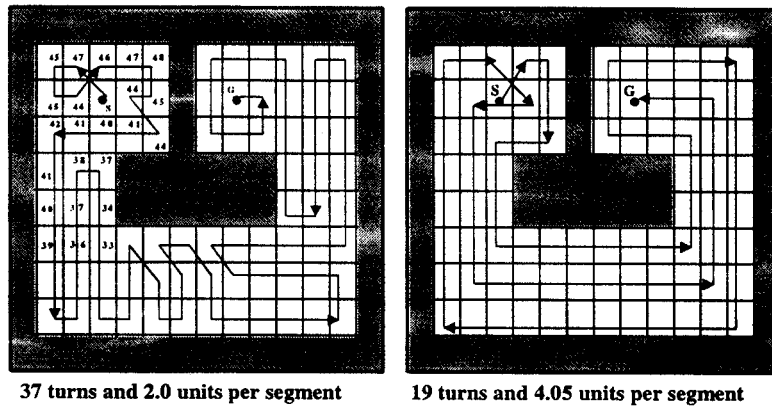


Figure 7. Complete coverage by artificial potential field: a) sinuous path, b) smooth path.

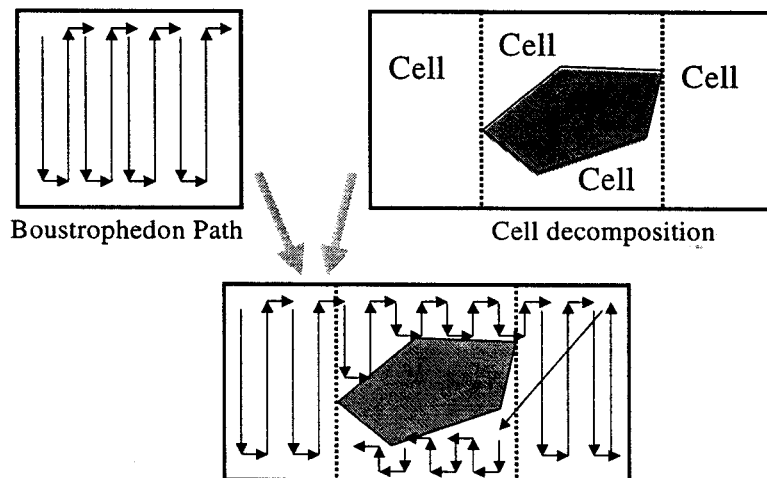


Figure 8. Combining templates and cell decomposition.

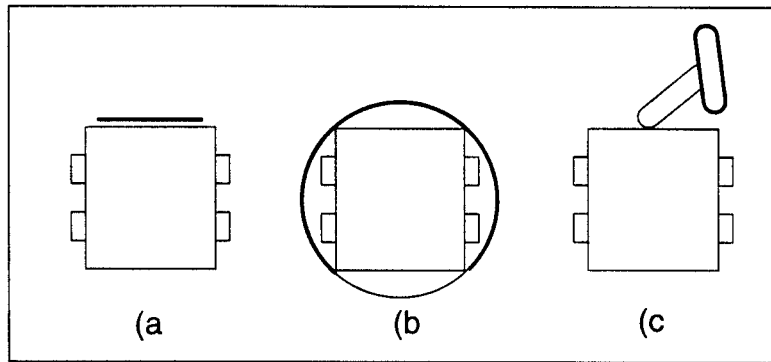


Figure 2. Basic shapes for a home robotic cleaner.

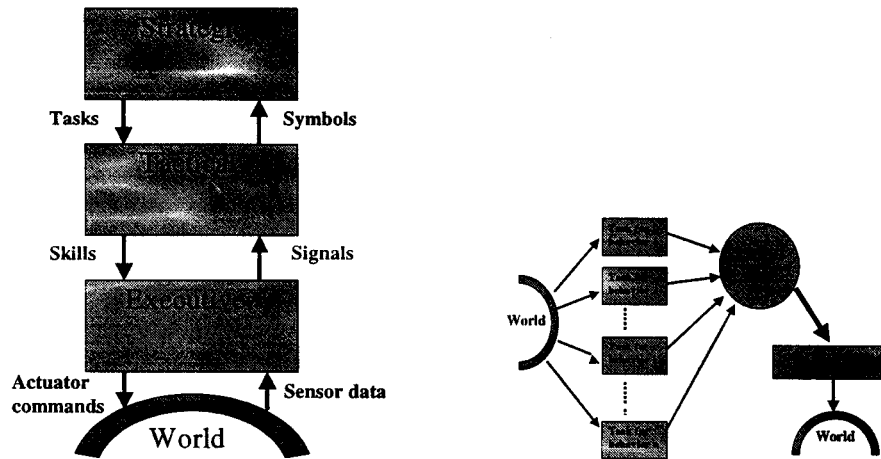


Figure 3. Typical control architectures: a) deliberative, b) behavior-based.

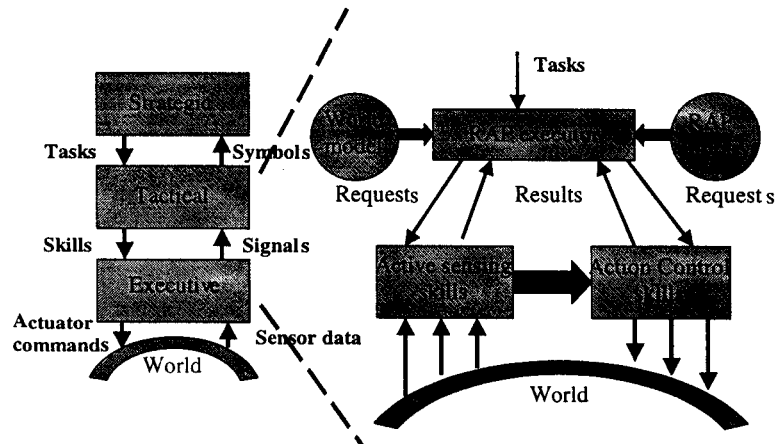


Figure 4. The RAP control architecture.

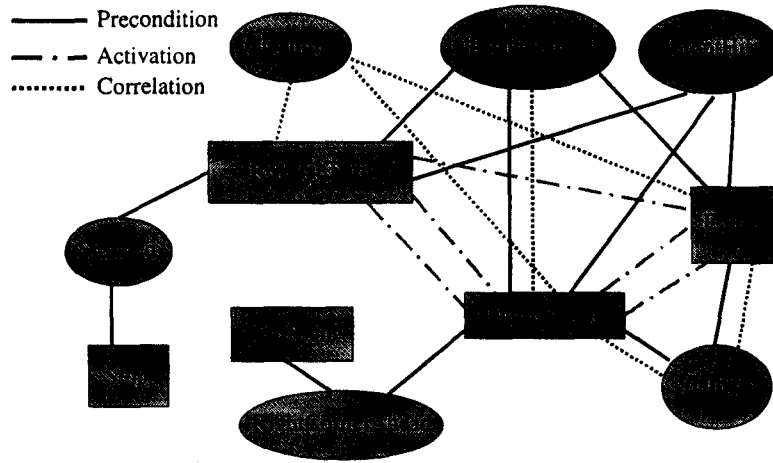


Figure 5. A segment of the ABBA control architecture.

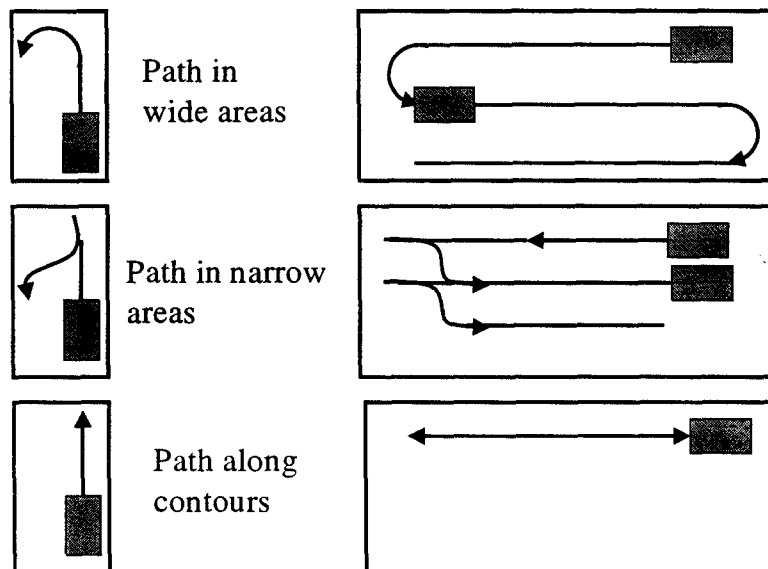


Figure 6. Coverage path planning using templates.